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Exploring LiDAR–RaDAR synergy—predicting aboveground biomass in a southwestern ponderosa pine forest using LiDAR, SAR and InSAR

Peter Hyde [a,*], Ross Nelson [b], Dan Kimes [b], Elissa Levine [b]

[a] Science Systems and Applications, Lanham, MD, United States
[b] NASA's Goddard Space Flight Center, Greenbelt, MD, United States

Abstract

Scanning Light Detecting and Ranging (LiDAR), Synthetic Aperture Radar (SAR) and Interferometric SAR (InSAR) were analyzed to determine (1) which of the three sensor systems most accurately predicted forest biomass, and (2) if LiDAR and SAR/InSAR data sets, jointly considered, produced more accurate, precise results relative to those same data sets considered separately. LiDAR ranging measurements, VHF–SAR cross-sectional returns, and X- and P-band cross-sectional returns and interferometric ranges were regressed with ground-estimated (from dbh) forest biomass in ponderosa pine forests in the southwestern United States. All models were cross-validated. Results indicated that the average canopy height measured by the scanning LiDAR produced the best predictive equation. The simple linear LiDAR equation explained 83% of the biomass variability ($n = 52$ plots) with a cross-validated root mean square error of 26.0 t/ha. Additional LiDAR metrics were not significant to the model. The GeoSAR P-band ($\lambda = 86$ cm) cross-sectional return and the GeoSAR/InSAR canopy height (X–P) captured 30% of the forest biomass variation with an average predictive error of 52.5 t/ha. A second RaDAR–FOPEN collected VHF ($\lambda \sim 7.8$ m) and cross-polarized P-band ($\lambda = 88$ cm) cross-sectional returns, none of which proved useful for forest biomass estimation (cross-validated $R^2 = 0.09$, RMSE = 63.7 t/ha). Joint consideration of LiDAR and RaDAR measurements produced a statistically significant, albeit small improvement in biomass estimation precision. The cross-validated R^2 increased from 83% to 84% and the prediction error decreased from 26.0 t/ha to 24.9 t/ha when the GeoSAR X–P interferometric height is considered along with the average LiDAR canopy height. Inclusion of a third LiDAR metric, the 60th decile height, further increased the R^2 to 85% and decreased the RMSE to 24.1 t/ha. On this 11 km^2 ponderosa pine study area, LiDAR data proved most useful for predicting forest biomass. RaDAR ranging measurements did not improve the LiDAR estimates.

1. Introduction

Measuring biomass in forests is important for understanding the dynamics of climate change and other causes of disturbance (Skole et al., 1994). Carbon flux uncertainties are exacerbated by the lack of consistent observations (Myneni et al., 1997; Smith et al., 1993). Direct measurements, such as destructive sampling of carbon stocks, are expensive, while indirect estimates, such as NDVI, are often inaccurate (Anderson et al., 1993; Brown, 1997; Smith & Brand, 1983). Direct measurements of forest structure that are highly correlated with biomass include diameter at breast height (dbh), basal area, canopy height, and crown volume (Husch et al., 1982; Smith & Brand, 1983). Radio Detecting and Ranging (RaDAR) and Light Detecting and Ranging (LiDAR) systems make measurements of some of these variables directly, e.g., canopy height, and/or make measurements which can be used to infer these variables.

Numerous researchers, reviewed below, have shown that these different LiDAR or RaDAR measurements, considered separately, can be used to estimate forest biomass. The primary objective of this study is to determine if these different LiDAR

and RaDAR forest canopy measurements, considered jointly, produce more accurate, precise estimates of aboveground forest biomass. In other words, the primary objective of this study is to determine if there are any LiDAR–RaDAR synergies that can be exploited to improve forest biomass estimation accuracy and precision. The secondary objective is to determine which of the LiDAR height and RaDAR height and cross-sectional returns most accurately predict total aboveground forest biomass in arid, relatively heterogeneous ponderosa pine stands.

Recent advances in instrumentation and techniques are producing estimates of biomass with unprecedented accuracies in even the most densely forested ecosystems. Traditionally, these attributes have been measured in the field using handheld equipment. Field methods are accurate but are time-consuming and therefore limited to either mapping at fine scales or relatively sparse sampling at the landscape scale. Multi-spectral (Hyyppa et al., 1998) and hyper-spectral remote sensing (Pu & Gong, 2004) have been used to map some aspects of structure at moderate resolution and broad scales. However, passive optical sensors have difficulty penetrating beyond upper forest layers (Weishampel et al., 2000) and are better suited for mapping horizontal components, such as land cover type. Synthetic aperture radar (SAR) and interferometric synthetic aperture radars (InSARs) can provide measures of vertical structure at landscape scales at varying degrees of accuracy. Ranson and Sun (1994, 2000) used a ratio of P- and C-bands and the HV polarization

(PHV/CHV) as well as L to C ratios (LHV/CHV) to predict biomass in boreal forests. Ranson et al. (1995) found a direct correlation between biomass and X and L-band with HV polarization (LHV/CHV) backscatter, again in a boreal forest. Many other studies (e.g., Baker et al., 1994; Green et al., 1996; Harrell et al., 1995, 1997; Hyyppa et al., 1997; Kasischke et al., 1995; LeToan et al., 1992; Wang et al., 1995) reporting accurate results for biomass retrieval are in plantations or in very simple (in terms of either physiognomy or floristics or both) forest types. SAR and InSAR appear to be suited for structurally homogeneous, simple forest types at the present time (Kasischke et al., 1997), although advances in technology should improve estimates in other ecosystem types (Treuhaft & Cloude, 1999; Treuhaft & Siqueira, 2000).

Light detecting and ranging (LiDAR) provides highly accurate measurements of forest structure (Drake et al., 2002; Hyde et al., 2005; Lefsky et al., 1999; Nelson et al., 1984). Due to the high cost of flight time, the need to limit scanning to near nadir in order to prevent ranging errors, and the presence of coverage gaps due to aircraft pitch and roll, many LiDAR studies provide samples at the stand level (Naesset, 2004) or image small areas (Wulder & Seeman, 2003); most missions do not provide the same wall-to-wall coverage at the same scale as a Landsat TM scene or SAR image.

The optimal strategy for mapping forest structure would include the finely-detailed measurements of the vertical dimension that currently only field sampling provides as well as the broad spatial coverage and lower cost per unit area provided by remote sensing. Although no single technology is capable of providing this level of forest structural information at the present time, improvements in RaDAR and LiDAR will likely lead to broad-scale mapping of vertical structure in the near future. In the meantime, it is possible to map forest structure at intermediate scales by statistically combining or fusing information from multiple sensors to take advantage of the highly detailed vertical measurements provided by LiDAR, the broad scale mapping capabilities of passive optical sensors, and the coarse sensitivity to horizontal and vertical structure afforded by RaDAR data sets. Combining information from multiple sensors, or data fusion, has yielded promising results for the estimation of forest structural characteristics (Wulder et al., 2004). Hudak et al. (2002) combined regression and co-kriging models from LiDAR and multispectral data; the results were more accurate than either data set alone. Wulder and Seeman (2003) used texture metrics from Landsat TM images to improve LiDAR estimates of canopy height (from 61% to 67% variability explained). Slatton et al. (2001) combined LiDAR data with InSAR to improve the estimates of vegetation heights relative to InSAR alone. Hyde et al. (in press) combined LiDAR, X band SAR, a DEM, and multispectral (ETM+ and Quickbird) for improved canopy height and biomass estimation; X-band SAR was less accurate than LiDAR and did not add much explanatory power. Moghaddam et al. (2002) found that combining Landsat TM and several RaDARs was more accurate in predicting ground-based measurements of forest structure than any single sensor alone.

6. Conclusion

Our results suggest that the most effective sensor to estimate biomass in open ponderosa pine is LiDAR. This is not unexpected, as LiDAR usually provides a direct, unambiguous range to target where the top of the canopy and the ground are clearly defined. This produces a direct physical measurement,

canopy height, which is highly correlated with biomass. GeoSAR, with both X- and P-bands, is capable of making a similar direct physical measurement. However, the ranges are sufficiently ambiguous to produce several meters of uncertainty. It is possible that given the relative openness of the canopy and the size of the individual trees, X-band is penetrating into the canopy. In a relatively short-statured forest such as our study area, this height error leads to reasonably large errors in biomass estimation. It is likely that GeoSAR would perform better in a taller forest, where the height errors are small relative to the total canopy height.

The volumetric responses from GeoSAR are more indirect physical measurements, perhaps more influenced by foliar orientation or wetness (e.g., Harrell et al., 1997) than tree biomass and therefore are less predictive. Also, we were only able to acquire HH and VV polarizations for GeoSAR X and P, respectively. HV or VH polarizations have been shown to be much more effective for biomass estimation; they were simply unavailable to us for this study. Somewhat surprising, the UHF band from the FOPEN SAR, similar in wavelength to the P-band image from GeoSAR, did not produce similar results; we suspect that the reason was a scale mismatch (see below). We are not surprised that FOPEN VHF was inaccurate for biomass retrieval at this scale; recall that it is designed to locate vehicles and unexploded ordinance below canopies. We do not consider this to be a system or FOPEN VHF failure; we purposely misapplied the tool because it was available, to verify that VHF held little in the way of biomass predictability. We merely confirm the fact that it does not. We understand that the CARABAS-II system, which also operates in the VHF range, produced accurate estimates of biomass (Fransson et al., 2000; Smith & Ulander, 2000); however, the field plots were located in a "relatively homogeneous forest" in pure stands of over 2 ha. There are differences among VHF RaDARs: CARABAS operates in the 20–90 MHz range (15 to 3.3 m) while FOPEN is down toward the lower end at 25–52 MHz (7.8 m). We speculate that most of the CARABAS biomass measurement capability exists up in the shorter wavelengths, while FOPEN, designed (for the Department of Defense) to penetrate forest canopies to find targets under trees, has a wavelength range too large to assess standing forest biomass. The largest ponderosa pine stems were on the order of half the wavelength of FOPEN, so much of the pp forest was, in essence, transparent to FOPEN. Had CARABAS flown Arizona, their shorter wavelengths may have interacted linearly with the ponderosa pine stems.

Therefore, if one had to select a single sensor for estimating biomass in this study area with this configuration of field plots, LiDAR would be the sensor of choice. Although inclusion of the GeoSAR–InSAR height along with the LiDAR height was statistically significant, we feel that it is of little practical utility relative to LiDAR alone. The addition of GeoSAR would improve the accuracy of the estimate, but only very slightly and at the cost of increased acquisition expenditures and processing time. It is possible that there was something unusual about the surface wetness (e.g., Harrell et al., 1997) that produced such poor RaDAR results and that having additional RaDAR images would in fact add additional structural information in other locations or meteorological conditions. However, since LiDAR produced biomass estimates at such high levels of accuracy, there is not much more room for improvement for biomass retrieval in this study area. Instead, future efforts could be directed towards taking better advantage of the broader coverage of RaDAR and devise a LiDAR sampling scheme of that coverage to produce a more comprehensive biomass map.